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Signatures of Scalar Top with R-parity Breaking Coupling at HERA

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ABSTRACT

In the framework of the minimal supersymmetric standard model with an R-parity breaking coupling of the scalar top quark (stop) we investigate production processes and decay properties of the stop at HERA energies. The model is characterized by a light stop possibly lighter than the other squarks. We show that the stop could be singly produced not only in the neutral current processes but also in associated processes whose final states contain some heavy flavor quarks, bottom and top quarks. These signatures would be useful to discriminate the stop from leptoquarks.

The search for the supersymmetric particles (sparticles) with masses below an order of the magnitude of 1TeV is one of the most important purpose of the present collider experiments. For this purpose theoretical physicists should give answers to following questions ; i) "which sparticle will be discovered first?" and ii) "what signature will be expected in such sparticle production?" Answers are obviously model dependent. The simplest model is the minimal supersymmetric standard model (MSSM) with conserved R-parity [1] ;

$$R \equiv (-)^{2S+3B+L}, \tag{1}$$

where S, B and L denote the spin, baryon and lepton numbers, respectively. In the model the sparticle expected to be discovered first, i.e., the lightest charged sparticle, is the slepton $\widetilde{\ell}$, the lighter chargino $\widetilde{W}_1$ or the stop $\widetilde{t}_1$. Irrespective of kinds of the lightest

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charged sparticles, there is a distinctive signature from the sparticle production, the large missing energies $\not{E}$ carried off by the lightest sparticle (LSP). The neutralness and the R-parity conservation guarantee the stablility and the very weak interaction with the matter in the detector.

Besides the MSSM with the conserved R-parity, there are models with the R-parity breaking (RB) couplings in the superpotential [2],

$$W_{\not{R}} = \lambda_{ijk} L_i L_j \overline{E}_k + \lambda'_{ijk} L_i Q_j \overline{D}_k + \lambda''_{ijk} \overline{U}_i \overline{U}_j \overline{D}_k, \tag{2}$$

where L, E, Q, U and D denote the appropriate chiral supermultiplets and $i \sim k$ are generation indices. We should note that these couplings are not forbidden by the gauge symmetry as well as by the supersymmetry. The first two terms violate the lepton number L and the last term violates the baryon number B. Consequently, the RB couplings in the supersymmetric models may be required in order to explain the cosmic baryon number violation, the origin of the masses and the magnetic moments of neutrinos and some interesting rare processes in terms of the L and/or B violation. Here we should keep in mind that we have to take the RB couplings as λ, $\lambda' \ll 1$ or $\lambda'' \ll 1$ to guarantee the stability against the fast proton decay. If we take sizable RB couplings the LSP can decay into the ordinary particles. In this case the typical signatures of the sparticle production would be multi-jets and/or multi-leptons instead of the large $\not{E}$.

Here we focus our attention on the stop $\widetilde{t}_1$ and investigate its production mechanisms and decay processes realized at HERA in the framework of the MSSM with the RB couplings of the stop. The RB couplings $W = \lambda'_{1jk} L_1 Q_j \bar{D}_k$ originated from the second term of the RB superpotential (2) are the most suitable for the ep collider experiments at HERA because the squarks will be produced through the s-channel in the e-q sub-processes. In the MSSM the stop mass could be lower than that of the other squarks in a model [3] because of the high expected mass of the top quark. The expected mass of the stop could be within the reach of HERA. The production of squarks with RB couplings in the first and second generation at HERA has been discussed extensively in Ref. [4].

In previous papers [5, 6, 7, 8] we have considered the stop $\widetilde{t}_1$ production through the s-channel in neutral current (NC) processes :

$$ep \to (\widetilde{t}_1 X) \to eqX, \tag{3}$$

and we have shown that we could get a clear signal as a sharp peak in the Bjorken variable x distribution. However, one of the leptoquarks $\widetilde{S}_{1/2}$ [9] with the charge $Q = -2/3$ would give the same signature as that of the RB stop, if the stop has BR($\widetilde{t}_1 \to ed$)$\simeq$100%. Note that this situation corresponds to the case of $m_{\widetilde{t}_1} < m_t + m_{\widetilde{Z}_1}$, $m_b + m_{\widetilde{W}_1}$. In this case it is difficult to discriminate the stop from the leptoquark $\widetilde{S}_{1/2}$. In this paper we generalize our calculation including the case of $m_{\widetilde{t}_1} > m_t + m_{\widetilde{Z}_i}$ or $m_{\widetilde{t}_1} > m_b + m_{\widetilde{W}_k}$ because HERA could search the heavy stop with mass $m_{\widetilde{t}_1} \lesssim$ 300GeV. We search for a possible experimental observable in the RB stop production in ep collisions.

In the framework of the MSSM, scalar fermion mass matrices in the ($\widetilde{f}_L$, $\widetilde{f}_R$) basis are expressed by

$$\mathcal{M}^2_{\widetilde{f}} = \begin{pmatrix} m^2_{\widetilde{f}_L} & a_f m_f \\ a_f m_f & m^2_{\widetilde{f}_R} \end{pmatrix}, \tag{4}$$

where $m_{\widetilde{f}_{L,R}}$ and a_f are the SUSY mass parameters and m_f denote the ordinary fermion masses. We can see from Eq. (4) that for the sleptons and the squarks except for the stops, the left and right handed sfermions are mass eigenstates in good approximation owing to small fermion masses in the off-diagonal elements of the mass matrices. On the other hand, the large mixing between the left and right handed stops will be expected because of the large top-quark mass [3], and the mass eigenstates are expressed by

$$\begin{pmatrix} \widetilde{t}_1 \\ \widetilde{t}_2 \end{pmatrix} = \begin{pmatrix} \widetilde{t}_L \cos\theta_t - \widetilde{t}_R \sin\theta_t \\ \widetilde{t}_L \sin\theta_t + \widetilde{t}_R \cos\theta_t \end{pmatrix}, \tag{5}$$

where θ_t denotes the mixing angle of stops :

$$\sin 2\theta_t = \frac{2a_t\, m_t}{\sqrt{(m^2_{\widetilde{t}_L} - m^2_{\widetilde{t}_R})^2 + 4a_t^2\, m_t^2}}, \tag{6}$$

$$\cos 2\theta_t = \frac{m^2_{\widetilde{t}_L} - m^2_{\widetilde{t}_R}}{\sqrt{(m^2_{\widetilde{t}_L} - m^2_{\widetilde{t}_R})^2 + 4a_t^2\, m_t^2}}. \tag{7}$$

We can easily calculate the mass eigenvalues of the stops as

$$m^2_{\substack{\widetilde{t}_1 \\ \widetilde{t}_2}} = \frac{1}{2}\left[m^2_{\widetilde{t}_L} + m^2_{\widetilde{t}_R} \mp \left((m^2_{\widetilde{t}_L} - m^2_{\widetilde{t}_R})^2 + (2a_t m_t)^2\right)^{1/2}\right]. \tag{8}$$

We find that if SUSY mass parameters and the top mass are the same order of magnitude, the cancellation could occur in the expression for the lighter stop mass Eq. (8). Moreover, the diagonal mass parameters $m^2_{\widetilde{t}_L}$ and $m^2_{\widetilde{t}_R}$ in Eq.(4) have possibly small values owing to the large negative contributions proportional to the top quark Yukawa coupling which is determined by the renormalization group equations in the mininal supergravity GUTs [10]. So we get one light stop $\widetilde{t}_1$ lighter than the first and the second generation squarks for a wide range of the SUSY parameters. Note that $\widetilde{t}_1$ could be even lighter than the top quark. After the mass diagonalization we can obtain the interaction Lagrangian in terms of the mass eigenstate $\widetilde{t}_1$. In particular the relevant RB coupling of the stop is obtained by

$$\mathcal{L}_{\rm int} = \lambda'_{131} \cos\theta_t (\widetilde{t}_1 \bar{d} P_L e + \widetilde{t}_1^{*} \bar{e} P_R d), \tag{9}$$

which is originated from the second term of the RB superpotential (2). The coupling (9) is the most suitable for the ep collider experiments at HERA because the stop will be produced through the s-channel in the e-d sub-processes. For simplicity we take λ'_{131} to be only non-zero coupling parameter in the following. The upper bound on the strength of copling λ'_{131} has been investigated through the low energy experiments [2] and the neutrino physics [11]. The most stringest present bound, $\lambda'_{131} \lesssim 0.3$, comes from the atomic parity violation experiments [2].

Actually, the stop can decay into the various final states :

$$\begin{aligned} \widetilde{t}_1 &\to t\, \widetilde{Z}_i && \text{(a)} \\ &\to b\, \widetilde{W}_k && \text{(b)} \\ &\to b\, \ell\, \widetilde{\nu} && \text{(c)} \\ &\to b\, \nu\, \widetilde{\ell} && \text{(d)} \end{aligned}$$

$$\begin{array}{llr} \rightarrow & b\,W\,\widetilde{Z}_i & \text{(e)} \\ \rightarrow & b\,f\,\overline{f}\,\widetilde{Z}_i & \text{(f)} \\ \rightarrow & c\,\widetilde{Z}_1, & \text{(g)} \\ \rightarrow & e\,d, & \text{(h)} \end{array}$$

where $\widetilde{Z}_i$ ($i = 1 \sim 4$), $\widetilde{W}_k$ ($k = 1, 2$), $\widetilde{\nu}$ and $\widetilde{\ell}$, respectively, denote the neutralino, the chargino, the sneutrino and the slepton. (a) $\sim$ (g) are the R-parity conserving decay modes, while (h) is realized by the RB coupling (9). If we consider the RB coupling λ'_{131} > 0.01, which corresponds to the coupling strength detectable at HERA, the decay modes (c) to (g) are negligible due to their large power of α arising from multiparticle finel state or one loop contribution. So there left the two body modes (a), (b) and (h). The formulae of the decay widths for each mode are respectively given by

$$\begin{aligned} \Gamma(\widetilde{t}_1 \rightarrow t\,\widetilde{Z}_i) \qquad &= \frac{\alpha}{2m^3_{\widetilde{t}_1}}\lambda^{1/2}(m^2_{\widetilde{t}_1}, m^2_t, m^2_{\widetilde{Z}_i}) \\ &\times \left[\left(|F_L|^2 + |F_R|^2\right)\left(m^2_{\widetilde{t}_1} - m^2_t - m^2_{\widetilde{Z}_i}\right) - 4m_t m_{\widetilde{Z}_i}\mathrm{Re}\,(F_R F_L^*)\right], \qquad (10) \\ F_L &\equiv \frac{m_t N'^*_{i4}\cos\theta_t}{2m_W \sin\theta_W \sin\beta} + e_u\,(N'^*_{i1} - \tan\theta_W N'^*_{i2})\sin\theta_t, \qquad (11) \\ F_R &\equiv \left(e_u N'_{i1} + \frac{1/2 - e_u\sin^2\theta_W}{\cos\theta_W\sin\theta_W}N'_{i2}\right)\cos\theta_t - \frac{m_t N'_{i4}\sin\theta_t}{2m_W\sin\theta_W\sin\beta}, \qquad (12) \end{aligned}$$

$$\begin{aligned} \Gamma(\widetilde{t}_1 \rightarrow b\,\widetilde{W}_k) \qquad &= \frac{\alpha}{4\sin^2\theta_W m^3_{\widetilde{t}_1}}\lambda^{1/2}(m^2_{\widetilde{t}_1}, m^2_b, m^2_{\widetilde{W}_k}) \\ &\times \left[\left(|G_L|^2 + |G_R|^2\right)\left(m^2_{\widetilde{t}_1} - m^2_b - m^2_{\widetilde{W}_k}\right) - 4m_b m_{\widetilde{W}_k}\mathrm{Re}\,(G_R G_L^*)\right], \qquad (13) \\ G_L &\equiv -\frac{m_b U^*_{k2}\cos\theta_t}{\sqrt{2}m_W\cos\beta}, \qquad (14) \\ G_R &\equiv V_{k1}\cos\theta_t + \frac{m_t V_{k2}\sin\theta_t}{\sqrt{2}m_W\sin\beta} \qquad (15) \end{aligned}$$

and

$$\Gamma(\widetilde{t}_1 \rightarrow e\,d) = \frac{\lambda'^2_{131}}{16\pi}\cos^2\theta_t m_{\widetilde{t}_1}, \qquad (16)$$

where $\lambda(x, y, z) \equiv x^2 + y^2 + z^2 - 2xy - 2yz - 2zx$. N'_{ij} and, V_{kl} and U_{kl} respectively read the neutralino and chargino mixing angles [1, 12]. The mixing angles as well as the masses $m_{\widetilde{Z}_i}$ and $m_{\widetilde{W}_k}$ are determined by the basic parameters in the MSSM (μ, $\tan\beta$, M_2), where M_2, $\tan\beta$ and μ denote the soft breaking mass for SU(2) gaugino, the ratio of two Higgs vacuum expectation values ($= v_2/v_1$) and the supersymmetric Higgs mass parameter, respectively. After all, we have input parameters (μ, $\tan\beta$, M_2, $m_{\widetilde{t}_1}$, θ_t, m_t, λ'_{131}) needed to calculate the decay widths and the branching ratio of the stop.

If the stop is heavy enough with mass $m_{\widetilde{t}_1} > m_t + m_{\widetilde{Z}_i}$ or $m_b + m_{\widetilde{W}_k}$ and the RB coupling is comparable with the gauge or the top Yukawa coupling, $\lambda'^2_{131}/(4\pi) \lesssim \alpha$, α_t, there is a parameter region where BR($\widetilde{t}_1 \rightarrow t\widetilde{Z}_i$) or BR($\widetilde{t}_1 \rightarrow b\widetilde{W}_k$) competes with BR($\widetilde{t}_1 \rightarrow ed$). In Fig. 1 we show $m_{\widetilde{t}_1}$ dependence of the branching ratio of the stop. Here we take m_t=135GeV, $\tan\beta$=2, λ'_{131}=0.1, θ_t=1.0 and (M_2(GeV), μ(GeV))= (50, -100) for (a)

and (100, -50) for (b). The output masses for the lightest neutralino and chargino are ($m_{\widetilde{Z}_1}$(GeV), $m_{\widetilde{W}_1}$(GeV))= (29, 71) for (a) and (42, 71) for (b). It is found that if the stop mass $m_{\widetilde{t}_1}$ is not too small, BR($\widetilde{t}_1 \to t\widetilde{Z}_i$) or BR($\widetilde{t}_1 \to b\widetilde{W}_k$) dominates over BR($\widetilde{t}_1 \to ed$). In Fig.2 we show the mixing angle θ_t dependence of the branching ratio. We find that the branching ratio depends also on θ_t.

In the case of BR($\widetilde{t}_1 \to ed$)$\simeq$100%, the most promising process is the stop $\widetilde{t}_1$ production through the s-channel in neutral current (NC) processes (3). We expect its clear signal as a sharp peak in the Bjorken parameter x distribution and the peak point corresponds to $x = m^2_{\widetilde{t}_1}/s$. As has been pointed out, it is well known that the similar peak in the x distribution could be expected to the leptoquark production at HERA [9]. We pointed out that the stop with the RB couplings could be discriminated from the most of leptoquarks by its distinctive properties ; 1)the x peak originated from the stop would exist only in the NC (not exist in the CC) process because there is no RB stop couplings to the neutrinos, 2)the e^+ beams are more favorable than the e^- beams [6, 8]. However, one of the leptoquarks $\widetilde{S}_{1/2}$ [9] with the charge $Q = -2/3$ would give the same signature as the RB stop. In fact H1 group at HERA has given the lower mass bound $m_{\widetilde{t}_1} \gtrsim$ 98GeV on the RB stop from the negative result for the leptoquark $\widetilde{S}_{1/2}$ search at 95% CL for λ'_{131} = 0.3 [13]. We should note that this bound is only applicable to BR($\widetilde{t}_1 \to ed$)$\simeq$100%, i.e. $m_{\widetilde{t}_1} < m_t + m_{\widetilde{Z}_1}$ and $m_b + m_{\widetilde{W}_1}$. We can see from Figs.1 and 2 that BR($\widetilde{t}_1 \to ed$)$\simeq$100% will not be realistic for the heavy stop. Even for λ'_{131} = 0.3 and $m_{\widetilde{t}_1}$ = 100GeV we get BR($\widetilde{t}_1 \to ed$)$\simeq$50%, where we take (m_t, $\tan\beta$, M_2, μ, θ_t) = (135GeV, 2, 50GeV, -100GeV, 1.0) for example. So we should be careful in converting the mass bound on the leptoquark $\widetilde{S}_{1/2}$ into the RB stop.

In the case BR($\widetilde{t}_1 \to ed$)$\ll$100% the other processes

$$ep \to t\widetilde{Z}_i X \tag{17}$$

and

$$ep \to b\widetilde{W}_k X \tag{18}$$

will have viable cross sections to which the stop contributes from the s-channel. The Feynman diagrams for these processes are depicted in Fig.3. In these diagrams, we consider also the virtual contributions of the selectron, sneutrino and d-squark with the same RB couplings λ'_{131}. The formulae for differential cross sections are given by

$$\begin{aligned}
&\frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}x\mathrm{d}Q^2}(ep \to t\,\widetilde{Z}_i X) = \\
&\frac{\alpha\lambda'^2_{131}}{8\hat{s}^2}\Bigg[\,|F_{\widetilde{e}}|^2\,\frac{(\hat{u}-m_t^2)(\hat{u}-m^2_{\widetilde{Z}_i})}{(\hat{u}-m^2_{\widetilde{e}_L})^2} + \left|F_{\widetilde{d}}\right|^2\frac{(\hat{t}-m_t^2)(\hat{t}-m^2_{\widetilde{Z}_i})}{(\hat{t}-m^2_{\widetilde{d}_R})^2} \\
&+\frac{\cos^2\theta_t\hat{s}}{(\hat{s}-m^2_{\widetilde{t}_1})^2+m^2_{\widetilde{t}_1}\Gamma^2_{\widetilde{t}_1}}\Big(\left(|F_L|^2+|F_R|^2\right)\left(\hat{s}-m_t^2-m^2_{\widetilde{Z}_i}\right)-4m_t m_{\widetilde{Z}_i}\mathrm{Re}\,(F_R F_L^*)\Big) \\
&+2\mathrm{Re}\left(F_{\widetilde{e}}F^*_{\widetilde{d}}\right)\frac{\hat{t}\hat{u}-m_t^2 m^2_{\widetilde{Z}_i}}{(\hat{u}-m^2_{\widetilde{e}_L})(\hat{t}-m^2_{\widetilde{d}_R})}
\end{aligned}$$

$$+\frac{2\cos\theta_t \hat{s}(\hat{s}-m^2_{\widetilde{t}_1})}{((\hat{s}-m^2_{\widetilde{t}_1})^2+m^2_{\widetilde{t}_1}\Gamma^2_{\widetilde{t}_1})(\hat{u}-m^2_{\widetilde{e}_L})}\mathrm{Re}\left(F^*_{\widetilde{e}}(F_R\hat{u}+F_L m_t m_{\widetilde{Z}_i})\right)$$
$$+\frac{2\cos\theta_t \hat{s}(\hat{s}-m^2_{\widetilde{t}_1})}{((\hat{s}-m^2_{\widetilde{t}_1})^2+m^2_{\widetilde{t}_1}\Gamma^2_{\widetilde{t}_1})(\hat{t}-m^2_{\widetilde{d}_R})}\mathrm{Re}\left(F^*_{\widetilde{d}}(F_R\hat{t}+F_L m_t m_{\widetilde{Z}_i})\right)\Bigg], \tag{19}$$

where $\hat{s}=xs$, $\hat{t}=-Q^2$ and

$$F_{\widetilde{e}} \equiv e_e N'_{i1} - \frac{1/2+e_e\sin^2\theta_W}{\cos\theta_W\sin\theta_W}N'_{i2}, \tag{20}$$
$$F_{\widetilde{d}} \equiv e_d N'_{i1} - e_d\tan\theta_W N'_{i2}. \tag{21}$$

$$\frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}x\mathrm{d}Q^2}(ep\to b\widetilde{W}_k X) =$$
$$\frac{\alpha\lambda'^2_{131}}{16\sin^2\theta_W\hat{s}^2}\Bigg[|V_{11}|^2\,\frac{(\hat{u}-m_b^2)(\hat{u}-m^2_{\widetilde{W}_k})}{(\hat{u}-m^2_{\widetilde{\nu}})^2}$$
$$+\frac{\cos^2\theta_t\hat{s}}{(\hat{s}-m^2_{\widetilde{t}_1})^2+m^2_{\widetilde{t}_1}\Gamma^2_{\widetilde{t}_1}}\left(\left(|G_L|^2+|G_R|^2\right)\left(\hat{s}-m_b^2-m^2_{\widetilde{W}_k}\right)-4m_b m_{\widetilde{W}_k}\mathrm{Re}\,(G_R G_L^*)\right)$$
$$-\frac{2\cos\theta_t\hat{s}(\hat{s}-m^2_{\widetilde{t}_1})}{((\hat{s}-m^2_{\widetilde{t}_1})^2+m^2_{\widetilde{t}_1}\Gamma^2_{\widetilde{t}_1})(\hat{u}-m^2_{\widetilde{\nu}})}\mathrm{Re}\left(V^*_{11}(G_R\hat{u}+G_L m_b m_{\widetilde{W}_k})\right)\Bigg]. \tag{22}$$

Figure 4 shows the stop mass dependence of the total cross sections for e^-p and e^+p collisions. It is found that to get larger cross section the e^+ beam is more efficient than the e^- one. This can easily be understood from the structure of the coupling. While the e^- collides only with sea $\bar{d}$-quarks in the proton, the e^+ collides with valence d-quarks. The difference of structure functions of the proton is naturally reflected in the cross sections. From Fig.4 we expect the detectable cross sections $\gtrsim$ 0.1pb for heavy stop with the mass $m_{\widetilde{t}_1}\lesssim$250GeV if we use the e^+ beam. Only the process $ep\to b\widetilde{W}_1X$ would be detectable for $m_{\widetilde{t}_1}\lesssim$170GeV so long as we use the e^- beam.

Next we should discuss the signature of these processes. Note that the LSP, the lightest neutralino $\widetilde{Z}_1$, will decay into R-even particles via the RB couplings [4]. In our model with only non-zero RB coupling λ'_{131}, $\widetilde{Z}_1$ decays into $bd\nu$ (see Fig. 5). Then the typical decay chains are

$$ep\to t\widetilde{Z}_1X\to(bW)(bd\nu)X\to(b(\ell\nu))(bd\nu)X \tag{23}$$

and

$$ep\to b\widetilde{W}_1X\to b(\ell\nu\widetilde{Z}_1)X\to b(\ell\nu(bd\nu))X. \tag{24}$$

In both processes one of typical signatures would be 2 b-jets + jet + ℓ + $\not{p}_T$. In Fig.6 we show the Monte Carlo events for the transverse momentum distribution of the scattered muon from the process (24) under the condition of the integrated luminosity $L=300\mathrm{pb}^{-1}$ for e^-p collisions. For simplicity, BR($\widetilde{W}_1\to\mu\nu\widetilde{Z}_1$) is assumed to be 1/9 [14]. Here we depict also the possible background muon events. They come from both charged current (CC) processes $e^-p\to\nu qX$ and W-gluon fusion (WGF) processes $e^-p\to\nu s\bar{c}X$, $\nu b\bar{c}X$, where use has been made of the generators LEPTO[15] and AROMA[16] with

JETSET[17], respectively. We find that the lower p_T cut for the scattered muon could be useful to distinguish the process (18) from the backgrounds. Since the multi-jet events accompanied by the high p_T muon are a distinctive signature for the RB stop production, the stop could be discriminated from the leptoquark $\widetilde{S}_{1/2}$ with the charge $Q = -2/3$.

Now we summarize our results obtained here. We have investigated various production processes of the stop at HERA energies in the framework of the MSSM with the RB coupling of the stop. If the stop is light enough $m_{\widetilde{t}_1} < m_t + m_{\widetilde{Z}_1}$, $m_b + m_{\widetilde{W}_1}$, the stop produced via RB interactions shows a sharp peak in the x distribution of neutral current processes due to its s-channel resonance. However, it is difficult to discriminate the stop from one of the leptoquarks $\widetilde{S}_{1/2}$. On the other hand, the other processes $ep \to t\widetilde{Z}_1 X$ and $ep \to b\widetilde{W}_1 X$ will have viable cross sections to which the stop contributes from the s-channel for $m_{\widetilde{t}_1} \gtrsim 100$GeV. In both processes one of the typical signatures would be 2 b-jets + jet + ℓ + $\not{p}_T$ owing to the LSP decay. One of the detectable signals of these processes is characterized by high p_T spectra of muons which are rather different from those of the background processes. Since this is a distinctive signature the stop could be discriminated from the leptoquark $\widetilde{S}_{1/2}$.

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Figure Captions

Figure 1: $m_{\widetilde{t}_1}$ dependence of branching ratio of stop. We take m_t=135GeV, $\tan\beta$=2, θ_t=1.0, λ'_{131}=0.1 and (M_2(GeV), μ(GeV))= (50, -100) for (a) and (100, -50) for (b).

Figure 2: θ_t dependence of branching ratio of stop. We take m_t=135GeV, $\tan\beta$=2, λ'_{131}=0.1, M_2=50GeV, μ=-300GeV and $m_{\widetilde{t}_1}$=200GeV.

Figure 3: Feynman diagrams for sub-processes $eq \to t\widetilde{Z}_i$ and $eq \to b\widetilde{W}_k$.

Figure 4: Stop mass dependence of total cross section. We take m_t=135GeV, θ_t=1.0, $\tan\beta$=2, λ'_{131}=0.1 M_2=100GeV, $m_{\widetilde{\ell}}$=200GeV, $m_{\widetilde{q}}$=300GeV and μ=-50GeV. Solid, sort-dashed, dotted and dashed lines correspond to $e^-p \to b\widetilde{W}_1^- X$, $e^+p \to \bar{b}\widetilde{W}_1^+ X$, $e^-p \to \bar{t}\widetilde{Z}_1 X$ and $e^+p \to t\widetilde{Z}_1 X$, respectively.

Figure 5: Feynman diagrams for LSP decay.

Figure 6: Monte Carlo events for transverse momentum distribution of scattered muon from $e^-p \to b\widetilde{W}_1 X$ (solid lines) together with backgrounds CC and WGF processes (short-dashed line). We take $m_{\widetilde{\ell}}$=200GeV, $m_{\widetilde{q}}$=300GeV, m_t=135GeV, θ_t=1.0, $\tan\beta$=2, λ'_{131}=0.1 M_2=100GeV, μ=-50GeV and integrated luminosity $L = 300\text{pb}^{-1}$.